A Long-term Intercomparison of Oceanic Optical Property Retrievals from MODIS/Terra and SeaWiFS

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Abstract

With over three years of contemporaneous MODIS and SeaWiFS data now available, there exists an unprecedented opportunity for intercomparison of global ocean color retrievals from two independent data sets. This study looks at the temporal trends in several, standard ocean color products derived from SeaWiFS and MODIS/Terra, to evaluate the long-term relative stability between the two sensors and to develop an understanding of their similarities and differences. The time-series analysis looks at variations in the mean value of water-leaving radiance and chlorophyll products over the period from March 2000 through December 2002, for both global and regional geographic areas. Results are presented in the form of temporal overlays for common products, as well as product ratios as a function of time. The analysis shows evidence of residual calibration artifacts in the MODIS products and a strong, latitudinally-dependent, seasonal cycle in the relative differences between the two sensors.

x.1 Introduction

The work presented here is a comparative analysis of mean global and regional oceanic optical property retrievals from two independent, spaceborne ocean color sensors: the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and the MODerate resolution Imaging Spectroradiometer (MODIS). The SeaWiFS instrument has been in continuous operation since September of 1997, while the MODIS instrument, flying on the Terra spacecraft, has been collecting data since March of 2000. With the recent reprocessings of both instrument data sets, there now exists over three years of consistently processed, contemporaneous MODIS and SeaWiFS data available through the Goddard Distributed Active Archive Center (GDAAC), providing an unprecedented opportunity for intercomparison of global ocean color retrievals from two independent sources. This study looks at the temporal trends in several ocean color products derived from SeaWiFS and MODIS to evaluate the long-term relative stability between the two sensors and develop an understanding of their similarities and differences. The time-series analysis looks at variations in the mean value of normalized water-leaving radiance and chlorophyll products over the period from 12 March 2000 through 31 December 2002, for both global and regional geographic areas. Results are presented in the form of temporal overlays for common products, as well as product ratios as a function of time.

x.2 Data Sources

The SeaWiFS data used in this analysis were standard, 9-km-resolution, Level-3 time-binned products from the 4th reprocessing, composited over 8-day periods. The MODIS data were standard, 4.6-km-resolution, Level-3 products from MODIS/Terra Oceans Collection 4.0, binned over the same 8-day periods. These Level-3, weekly data products for both SeaWiFS and MODIS are currently available from the GDAAC. It should be noted that some of the MODIS data used in this study are considered provisional. Due to the extensive, on-orbit characterization required to calibrate MODIS for ocean data processing, all data collected after the MODIS Oceans Collection 4.0 reprocessing (after March 19, 2002) are not fully corrected. Data collected prior to November 2000 are also considered provisional, due to the instability of the spacecraft and instrument during the first year of the Terra mission.

Several changes to the MODIS data were required to enable a bin-for-bin match-up with SeaWiFS. The first step was to convert the MODIS files to SeaWiFS-like Level-3 bin format. This was simply a reorganization of the HDF fields, as the SeaWiFS and MODIS formats use the same, sinusoidal binning approach. At this step, specific MODIS products were associated with standard SeaWiFS products, and any necessary unit conversions were performed. Only MODIS quality zero (QL=0) data were retained. The MODIS products chlor_a_2, nLw_412, nLw_443, nLw_488, and nLw_551, were associated with SeaWiFS products chlor_a, nLw_412, nLw_443, nLw_490, and nLw_555, respectively. The band associations are summarized in Table 1. Note that the algorithm for the chlor_a_2 product of MODIS (OC3M algorithm, O'Reilly et al., 2000) is very similar to that of the chlor_a product from SeaWiFS (OC4v4 algorithm, O'Reilly et al., 2000). The second step was to reduce the MODIS 4.6-km bin file to 9-km resolution, equivalent to standard SeaWiFS Level-3 bin resolution. This is effectively a 4-to-1 spatial averaging, weighted by the number of observations within each 4.6-km bin. The final step was to reduce the MODIS and SeaWiFS 9-km bin files to common bins. For a given 8-day period, only those bins that were filled in both the MODIS and the SeaWiFS files were retained in the final analysis. Filled bins are those for which one or more QL=0 retrievals were acquired.

x.3 Subset Definitions

With 8-day composited SeaWiFS and MODIS data products in an equivalent form, the data sets were further divided into several geographic subsets. Three global subsets were defined, corresponding to clear water, deep water, and coastal water. The deep-water subset consists of all bins where water depth is greater than 1000 meters. Clear water was defined as deep water where the retrieved chlorophyll is less than 0.15 mg m^{-3}. For the clear-water test, both SeaWiFS and MODIS retrievals were required to be below the chlorophyll threshold. Coastal water was defined as all bins where water depth is between 50 and 1000 meters, as defined by a shallow water mask and the deep water mask. Some caution should be exercised when comparing the clear-water subsetted data, as anomalously high chlorophyll retrievals from either sensor can significantly alter the geographic distribution of selected bins. In contrast, the deep-water and coastal subsets are purely geographic in selection criteria. The coastal subset, however, is more likely to contain regions of significant variability in water structure and atmospheric conditions, as well as Case-2 water types (Morel and Prieur, 1977) for which the bio-optical algorithms are invalid. These effects can be expected to increase retrieval uncertainty and thus result in larger differences between the two sensors. The deep-water subset is, therefore, the most stable subset for cross-sensor comparison of retrieved oceanic optical properties. The geographic extent of all three global subsets will vary, however, with the seasonal change in earth illumination and thus sensor imaging duty cycle.

In addition to the global subsets, six basin-scale subsets were analyzed. These included regions in the northern Pacific (PacN), northwestern Pacific (PacNW), southeastern Pacific (PacSE), northern Atlantic (AtlN), southern Atlantic (AtlS), and the southern Indian Ocean (IndS). In addition, a smaller region near Hawaii was defined. All of these subset regions were adopted from Fougnie et al. 2002, and their locations are listed in Table 2. Based on the results of the regional analysis, yet another group of subsets was defined to provide a systematic means for investigating latitudinally-dependent differences between the two sensors. A longitudinal segment of the Pacific from 170W to 150W was divided into 10-deg latitude zones. These zonal subsets are summarized in Table 3.

x.4 Trending Analysis

For each sensor, for each 8-day product, the filled bins associated with a particular subset were identified and used to compute the mean, standard deviation, and average observation time. Figure 1 shows an example of a typical trend plot derived from this analysis. For the upper panel of Figure 1, the common MODIS and SeaWiFS bins for the deep-water subset were spatially averaged for each 8-day-binned water-leaving radiance product, and the resulting means were then plotted as a function of time. The plot in the lower panel shows the same data as a ratio, with MODIS means normalized by SeaWiFS means. Similarly, Figure 2 shows the chlorophyll trends for the same deep-water subset. The solid vertical lines in the temporal trend plots are provided as a reference to indicate the transitions between MODIS Oceans calibration epochs. These epochs are the independent periods over which MODIS/Terra calibration corrections were derived and implemented by the MODIS Oceans group at the University of Miami (RSMAS). In most cases, these periods correspond with the calibration epochs used by the MODIS Calibration Support Team (MCST) for the adjustment of the Level-1B radiances, and they usually correspond with spacecraft safe-hold events or significant instrument state changes.

x.5 Discussion of Results

On average, the agreement between MODIS and SeaWiFS over the trended time-period is good. It is evident from the deep-water trend plots of Figure 1, however, that MODIS and SeaWiFS radiances deviate considerably in certain time-periods. Table 4 shows the mean and standard deviation of the global trends (i.e., the mean and standard deviation of the 8-day subset means). The table serves to illustrate both the good overall agreement and the higher time variability observed with MODIS. Note that at a wavelength of 551 nm, in clear water, MODIS shows a 4% temporal variability over the trend period (standard deviation relative to mean), while the equivalent SeaWiFS variability is just 2%. At shorter wavelengths, the difference is larger.

There is significant evidence to suggest that the elevated temporal variability observed in the MODIS products, relative to SeaWiFS, is an artifact of the MODIS characterization and processing. First, the long-term temporal stability of SeaWiFS is well established. The SeaWiFS calibration team makes use of monthly lunar observations to track and correct for time-dependent drifts in detector response. Based on this lunar calibration, the temporal degradation of SeaWiFS has been found to be well characterized as an exponential decay, and the change in responsivity over time has been shown to be highly predictable (Eplee et al., 2003a). Furthermore, the stability of the water-leaving radiance products from either sensor can be independently tested by evaluating the repeatability of the seasonal cycles observed in the temporal trends. While it is possible that the differences between SeaWiFS and MODIS are geophysical, due to the 90-minute difference in node crossing time, it can be expected that such effects (e.g., bi-directional reflectance) would be repeatable from year to year in accordance with the seasonally changing distribution of solar and viewing angles. The instruments may differ from one another, but they should be self-consistent in the absence of any major geophysical event. The deep-water annual repeatability plots presented in Figure 3, however, show that, while SeaWiFS is consistent from year to year, MODIS is highly variable. It should also be noted that the deviations between the MODIS and SeaWiFS trends often change character at intervals associated with MODIS Oceans calibration epochs. A good example of this coincidence is the discontinuity seen in the ratio trends of Figure 1 at the start of November 2000, a date that is directly related to the MODIS transition from A-side to B-side electronics. The large deviation that starts in late March of 2002 and ends at the end of May 2002 is known to be associated with a discrepancy between the measured solar diffuser calibration and the predicted Level-1B calibration factors applied at the time of processing (K. Kilpatrick, RSMAS, personal communication). This inconsistency between measured and predicted Level-1B calibration invalidated the in-flight Level-2 corrections and calibration factors derived previously by RSMAS. Based on the coincidence between MODIS calibration and processing changes and MODIS product deviations relative to SeaWiFS, and the observation that the seasonal cycles in the MODIS trends are inconsistent from year to year, it is likely that a significant portion of the temporal variability observed by MODIS is actually a calibration or instrument characterization artifact.

The regional subset trends provided in Figure 4 show that the relative agreement in retrieved water-leaving radiances between the two sensors varies geographically. The best agreement is found within the small Hawaii region and the two larger regions of the northern Pacific (of the three, only the PacNW region is shown in Figure 4, for brevity). This may be due to the fact that both SeaWiFS and MODIS are vicariously calibrated to the Marine Optical Buoy (MOBY), which is located near Lanai, Hawaii (Clark et al., 2001). The SeaWiFS calibration makes use of the MOBY measurements to derive a single gain adjustment for each band (Eplee et al., 2003b). The MODIS calibration includes a similar, overall gain correction within each calibration epoch, but it also makes use of the MOBY measurements and the relatively homogeneous waters of the northern Pacific to derive various instrument corrections. These corrections include mirror-side and scan-angle dependencies, and residual detector striping, all of which vary with time in accordance with the calibration epochs (Kearns et al., 2002). The regional trends suggest that the differences between the two sensors increase with distance from the common calibration region, which may be an indication that the MODIS calibration and post-launch instrument characterization is over-tuned to the northern Pacific region. The regions of the northern and southern Atlantic show many similarities with the global deep-water trends, but as the analysis progresses further south to the Indian Ocean region and the south eastern Pacific, the deviations between MODIS and SeaWiFS retrieved radiances increase, and a strong seasonality is evident in the ratio trends.

This apparent latitudinal dependence in the relative agreement between MODIS and SeaWiFS was the motivation for the zonal subset analysis, which is provided in Figure 5. The zonal trends clearly indicate that, as the evaluation progresses from the northern latitudes to the southern latitudes, the relative differences between MODIS and SeaWiFS increase and become strongly seasonal, with the largest differences occurring near the austral winter. Furthermore, the effect has a significant spectral dependence, with the blue bands of MODIS being significantly depressed relative to SeaWiFS. Unfortunately, there is little *in situ* data available to determine which instrument is more correct, but the zonal trends do show that, at southern latitudes below 30-deg south, the MODIS normalized water-leaving radiance measurements at 412 nm approach or even fall below the 551-nm radiances every July. Such a spectral dependence is normally associated with very turbid water, which is not common to the open oceans of the southern Pacific. The elevated seasonality in the water-leaving radiances retrieved by MODIS, relative to SeaWiFS, is most likely an artifact of the processing algorithms or instrument characterization. Based on discussion with RSMAS (R. Evans, personal communication), it is believed that the observed seasonal biases of the southern hemisphere may be due to limitations in the pre-launch characterization of polarization sensitivity for the MODIS/Terra mirror, which has significantly degraded since launch. RSMAS is currently exploring ideas for a post-launch re-characterization of the polarization sensitivity for MODIS/Terra.

The spectral dependence observed in the ratio trends indicates that MODIS/Terra Collection 4.0 chlorophylls will be biased high relative to SeaWiFS, for the Southern Hemisphere in the austral winter. This is illustrated in Figure 6, which shows the chlorophyll trends for the same zonal subsets. The relative bias in chlorophyll between SeaWiFS and MODIS for July in the southern Pacific is on the order of 50%, or 0.05 mg m^{-3} in absolute terms.

x.6 Summary

A long-term, contemporaneous time-series of global and regional mean normalized water-leaving radiance and chlorophyll retrievals from SeaWiFS and MODIS/Terra was developed and analyzed. The results show that, while SeaWiFS and MODIS products are similar on average, significant differences can be found which correlate with time and location. Some of the largest deviations between the two data sets are directly associated with periods over which the MODIS calibration or processing was changed. This observation, coupled with the fact that the seasonal cycle in global water-leaving radiances measured by SeaWiFS is highly repeatable from year to year while the MODIS seasonal cycle is not, suggests that a significant portion of the temporal variability in the water-leaving radiances measured by MODIS is not geophysical. The regional and zonal trends show that the deviations between MODIS and SeaWiFS increase with increasing southern latitude, and the product ratios show a strong seasonality. The spectral dependence of the radiance ratios results in MODIS chlorophyll retrievals that are as much as 50% higher than SeaWiFS in the Southern Hemisphere, with the greatest differences occurring near the austral winter.

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Band	SeaWiFS	MODIS
1	412	412
2	443	443
3	490	488
5	555	551

Table 1: *Band Correspondence (nm)*

Region ID	Minimum Latitude	Maximum Latitude	Minimum Longitude	Maximum Longitude
Hawaii	18.0	19.9	-158.5	-156.5
PacN	15.0	23.0	-180.0	-159.4
PacNW	10.0	22.7	139.5	165.6
PacSE	-44.9	-20.7	-130.2	-89.0
AtlN	17.0	27.0	-62.5	-44.2
AtlS	-19.9	-9.9	-32.3	-11.0
IndS	-29.9	-21.2	89.5	100.1

Table 2: *Regional Subset Definitions*

Region ID	Minimum Latitude	Maximum Latitude	Minimum Longitude	Maximum Longitude
PacN50	40.0	50.0	-170.0	-150.0
PacN40	30.0	40.0	-170.0	-150.0
PacN30	20.0	30.0	-170.0	-150.0
PacN20	10.0	20.0	-170.0	-150.0
PacN10	0.0	10.0	-170.0	-150.0
PacS10	-10.0	0.0	-170.0	-150.0
PacS20	-20.0	-10.0	-170.0	-150.0
PacS30	-30.0	-20.0	-170.0	-150.0
PacS40	-40.0	-30.0	-170.0	-150.0
PacS50	-50.0	-40.0	-170.0	-150.0

Table 3: *Zonal Subset Definitions*

		Chlorophyll-a		Band 1		Band 2		Band 3		Band 5	
Sensor	Subset	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
SeaWiS	Clear	0.076	0.0029	2.248	0.0672	1.886	0.0434	1.255	0.0189	0.299	0.0067
MODIS		0.079	0.0054	2.122	0.1971	1.798	0.1126	1.284	0.0443	0.317	0.0115
SeaWiS	Deep	0.185	0.0127	1.746	0.0547	1.533	0.0358	1.133	0.0188	0.336	0.0081
MODIS		0.178	0.0177	1.614	0.2167	1.426	0.1333	1.141	0.0547	0.345	0.0146
SeaWiS	Coastal	0.916	0.1962	0.832	0.0578	0.893	0.0429	0.875	0.0340	0.426	0.0224
MODIS		0.736	0.1216	0.825	0.1387	0.831	0.0926	0.878	0.0513	0.429	0.0261

Table 4: *Global Trend Statistics*

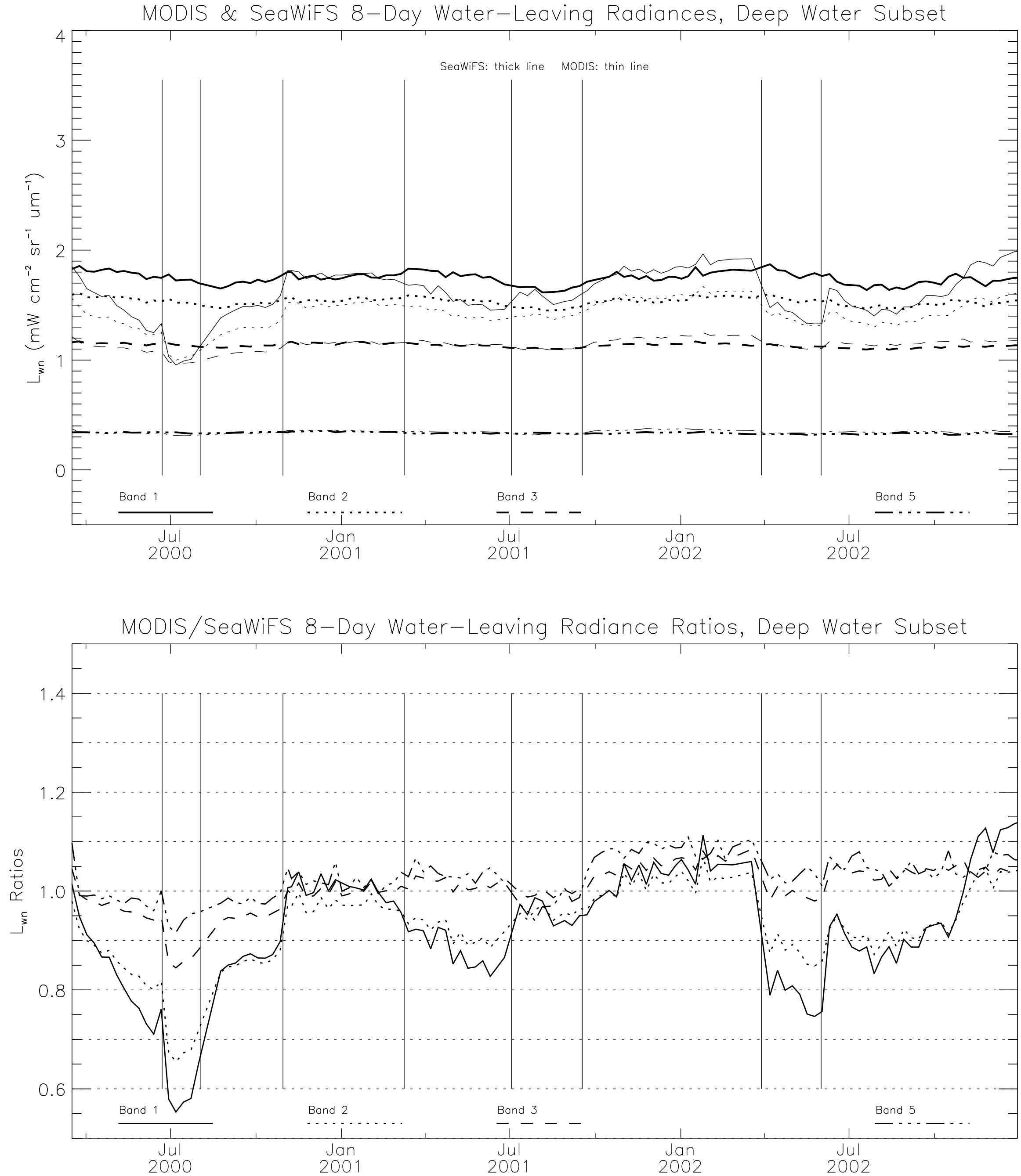

Figure 1: *MODIS and SeaWiFS normalized water-leaving radiance trends, March 2000 through December 2002. Different wavelength-bands are indicated by different line types. The upper panel shows MODIS and SeaWiFS trends as an overlay, with SeaWiFS indicated as the thick line and MODIS as the thin line. The lower panel shows the ratio of common bands between the two sensors. The solid vertical lines indicate epoch dates in the MODIS oceans calibration and characterization coefficients.*

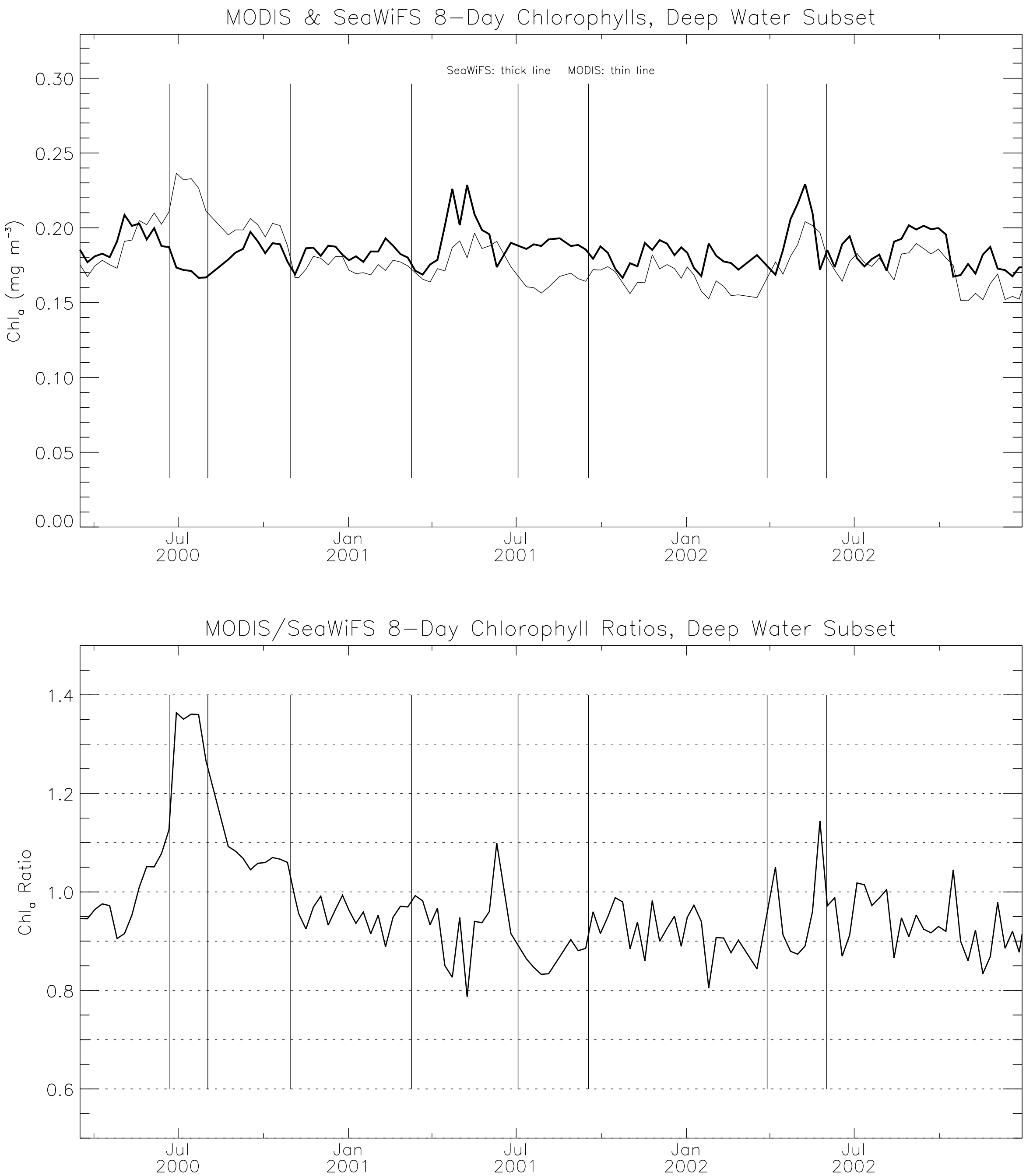

Figure 2: *MODIS and SeaWiFS chlorophyll trends, March 2000 through December 2002. The upper panel shows the MODIS and SeaWiFS trends as an overlay, with SeaWiFS indicated as the thick line and MODIS as the thin line. The lower panel shows chlorophyll ratio, with MODIS normalized by SeaWiFS. The solid vertical lines indicate epoch dates in the MODIS oceans calibration and characterization coefficients.*

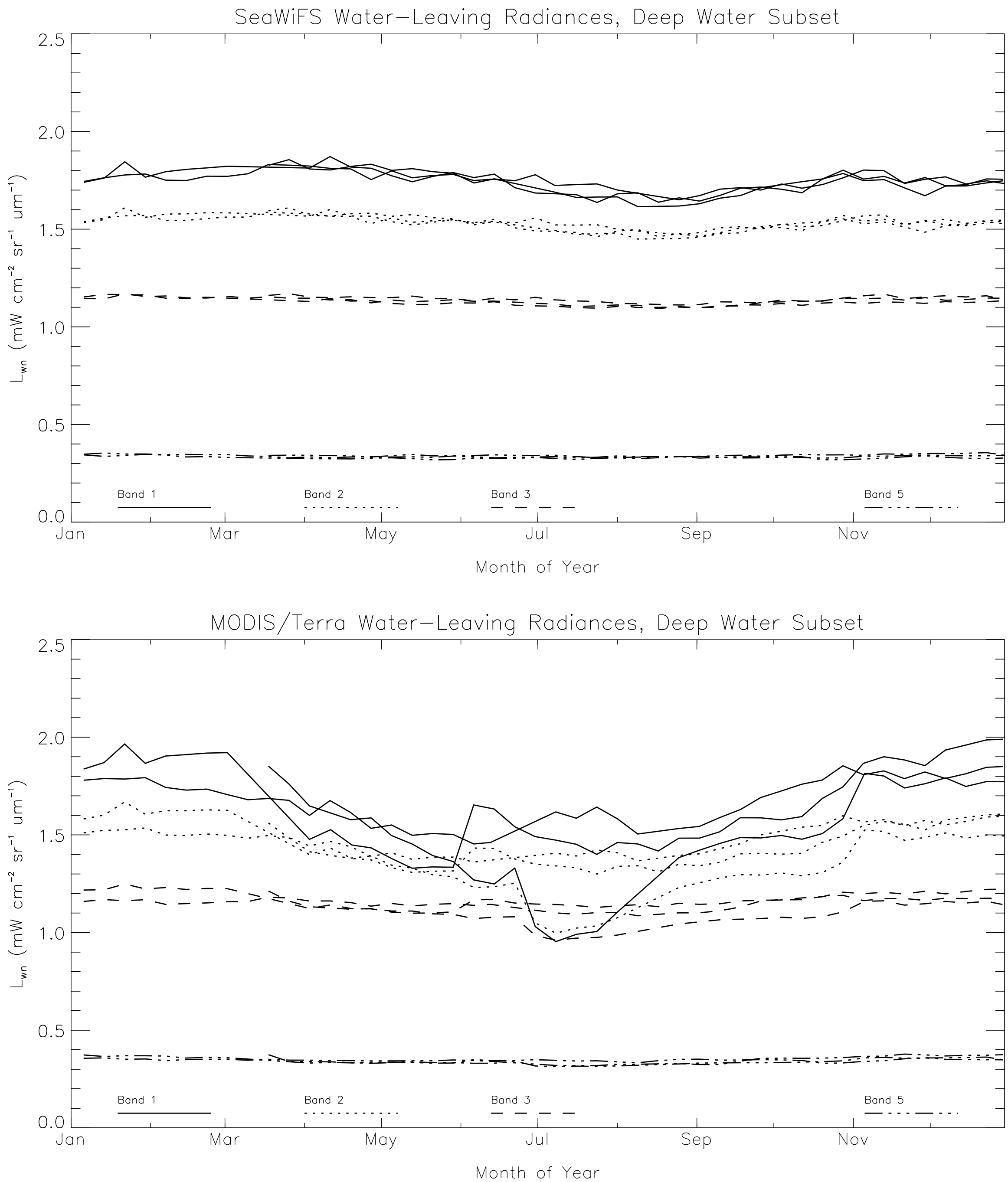

Figure 3: *MODIS and SeaWiFS normalized water-leaving radiance trends plotted to show the repeatability in the annual cycle. Different wavelength-bands are indicated by different line types. The upper panel shows the SeaWiFS and the lower panel shows MODIS.*

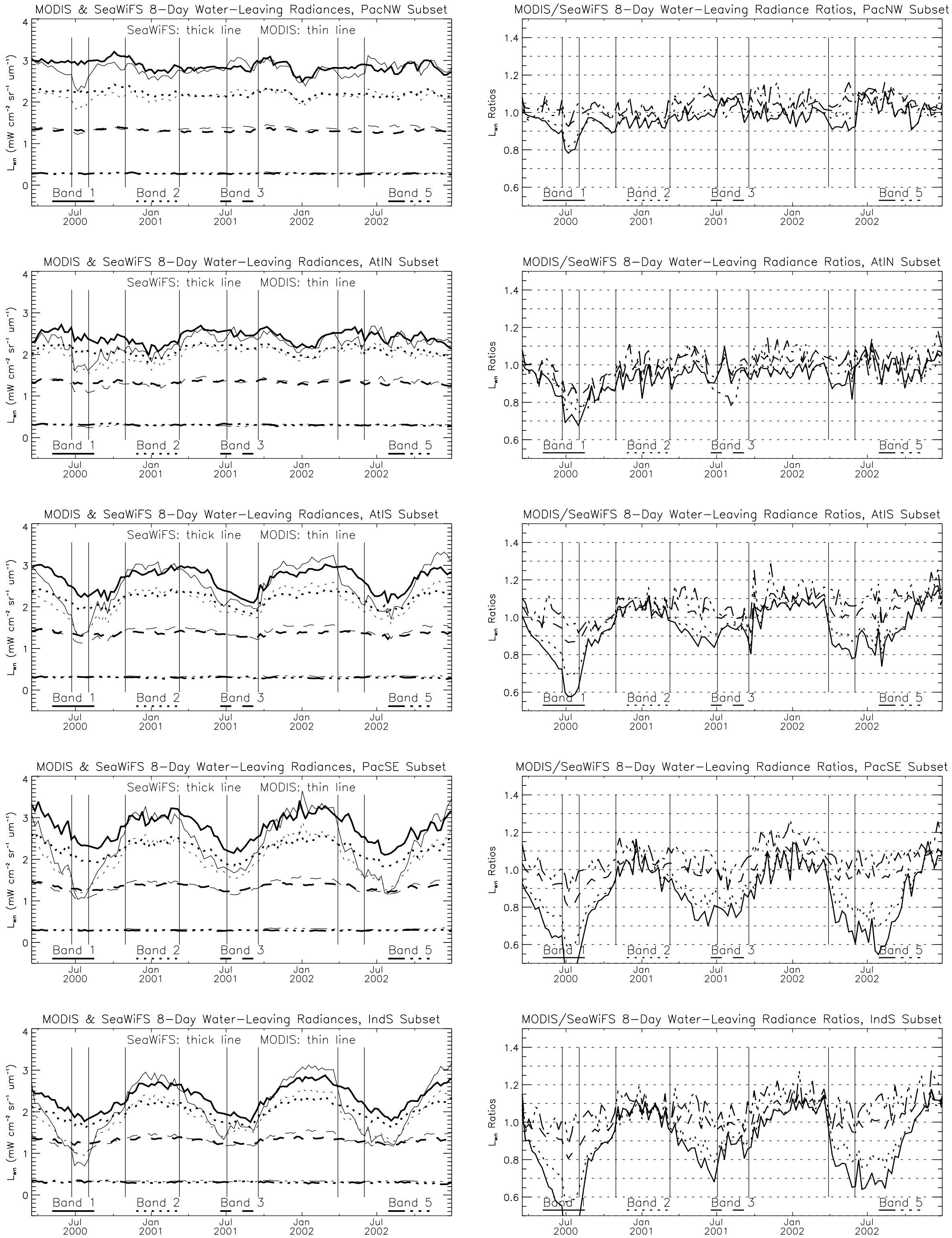

Figure 4: *MODIS and SeaWiFS normalized water-leaving radiance trends for the regional subsets. The left column shows the overlay of MODIS and SeaWiFS trends, with SeaWiFS indicated by the thicker line. The right column shows the radiance ratios between the two sensors. Wavelength bands are indicated by different line types.*

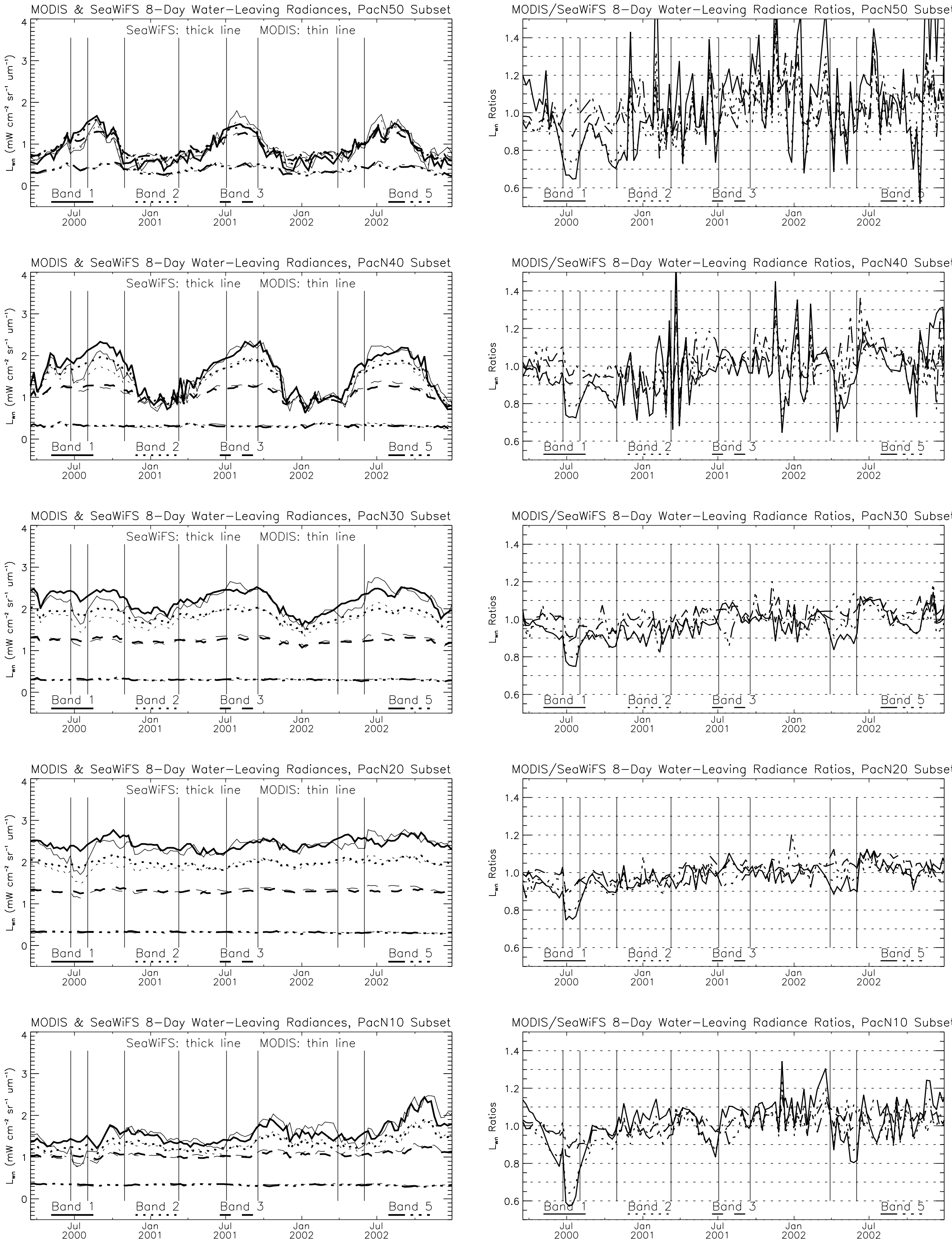

Figure 5a: *MODIS and SeaWiFS normalized water-leaving radiance trends for the northern latitudinal zones of the Pacific. The left column shows the overlay of MODIS and SeaWiFS trends, with SeaWiFS indicated by the thicker line. The right column shows the radiance ratios between the two sensors. Wavelength bands are indicated by different line types.*

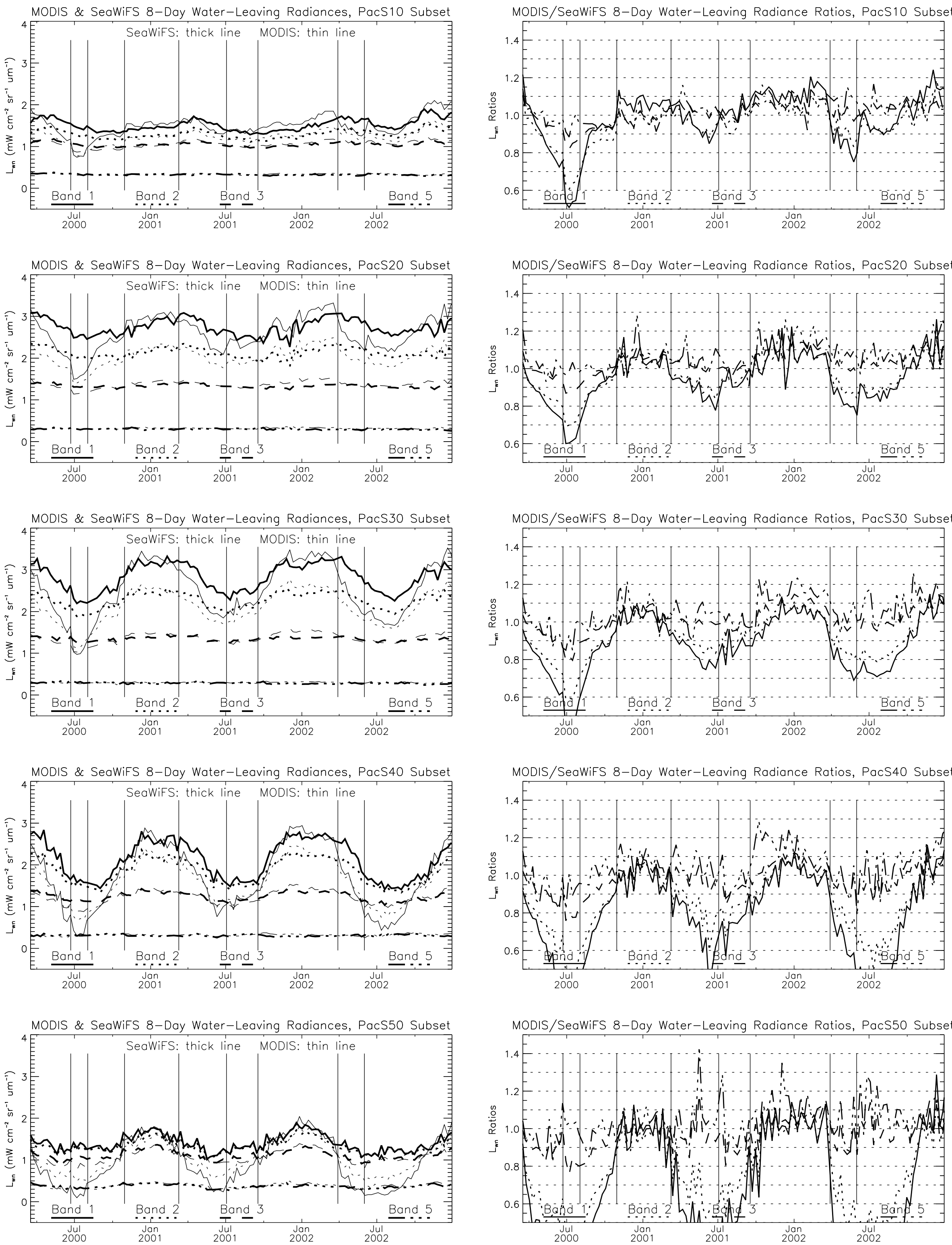

Figure 5b: *MODIS and SeaWiFS normalized water-leaving radiance trends for the southern latitudinal zones of the Pacific. The left column shows the overlay of MODIS and SeaWiFS trends, with SeaWiFS indicated by the thicker line. The right column shows the radiance ratios between the two sensors. Wavelength bands are indicated by different line types.*

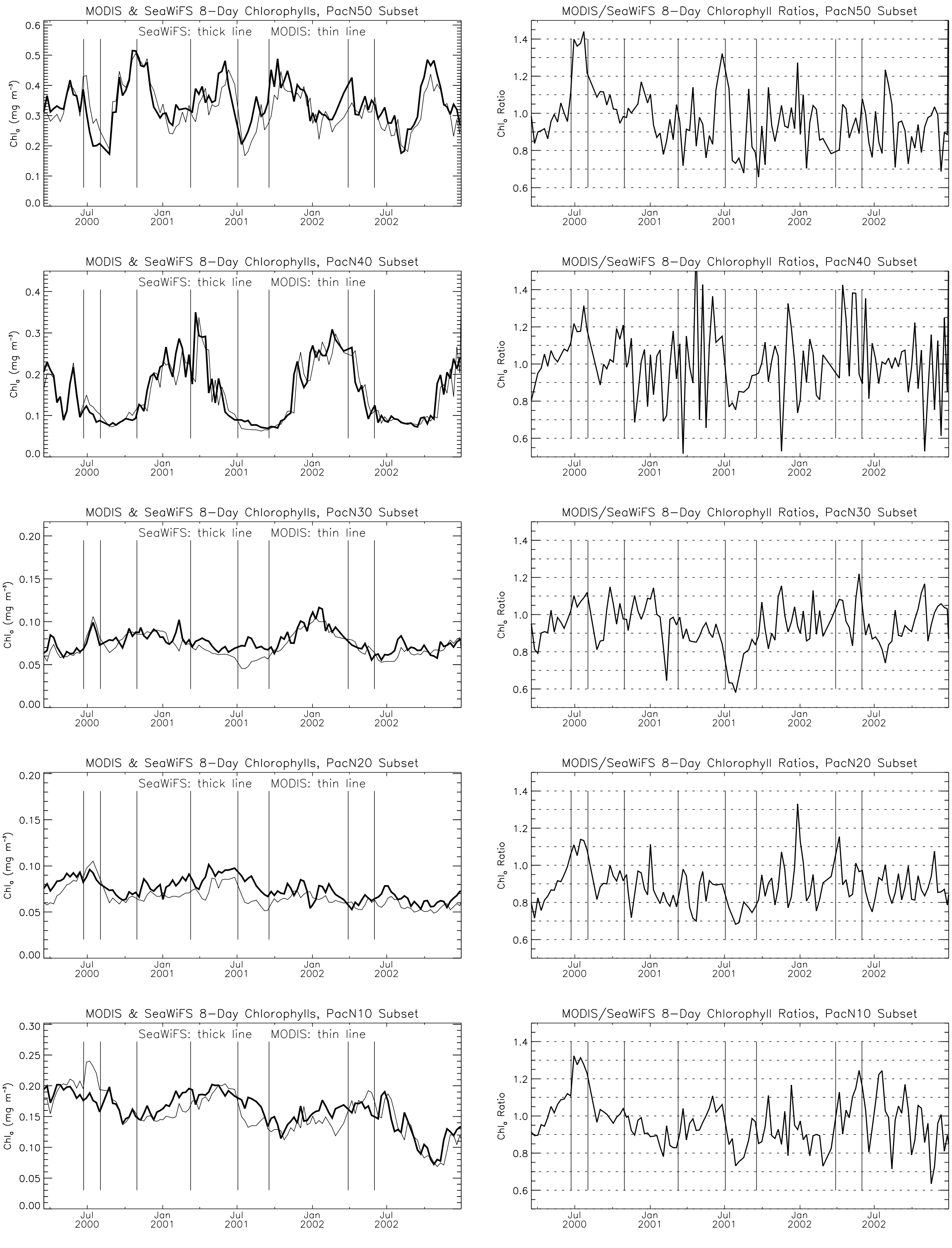

Figure 6a: *MODIS and SeaWIFS chlorophyll trends for the latitudinal zones of the northern Pacific. The left column shows the overlay of MODIS and SeaWiFS trends, while the right column shows chlorophyll ratios between the two sensors.*

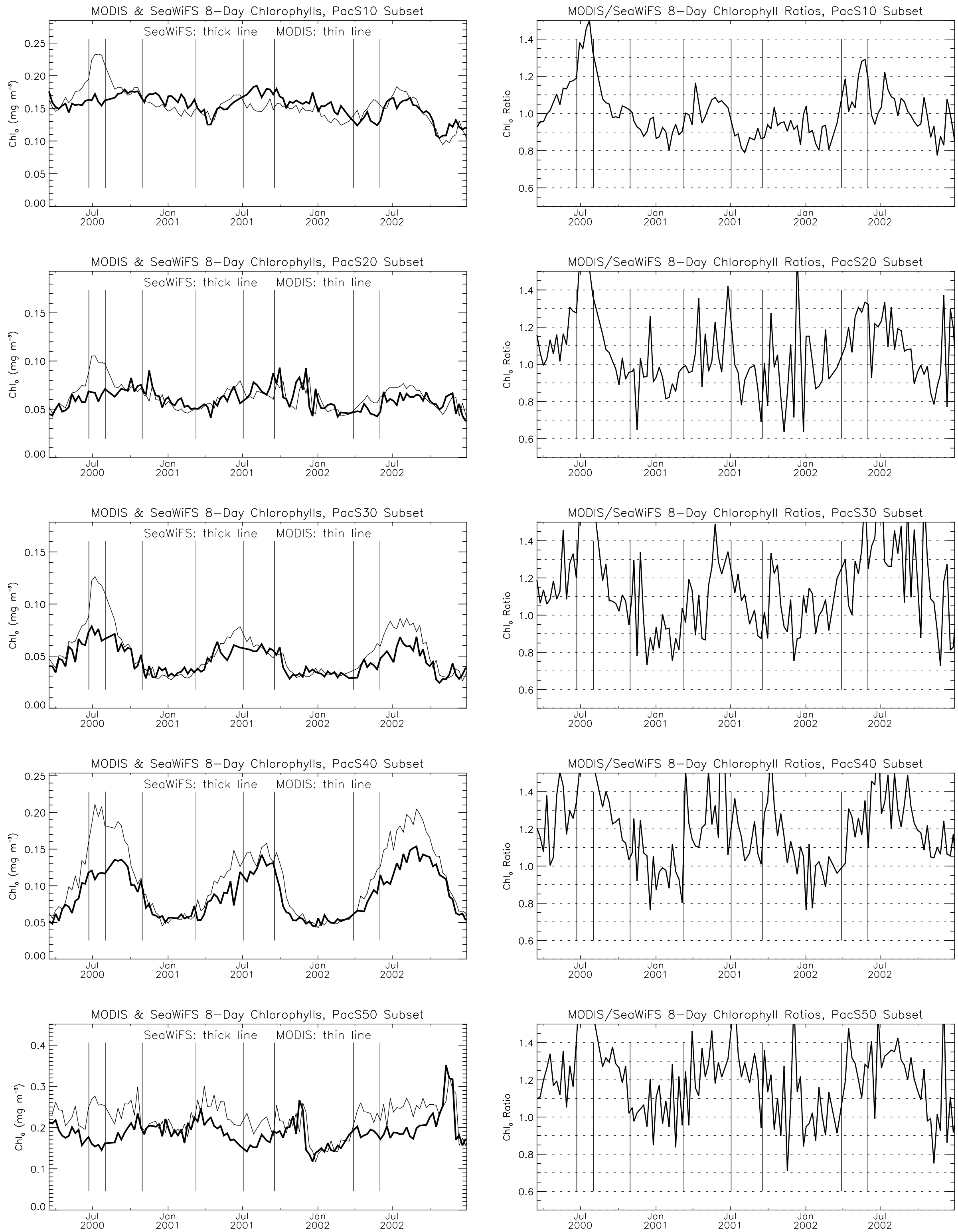

Figure 6b: *MODIS and SeaWIFS chlorophyll trends for the latitudinal zones of the southern Pacific. The left column shows the overlay of MODIS and SeaWiFS trends, while the right column shows chlorophyll ratios between the two sensors.*